Chapter 1
Introduction: Coral Bleaching - Patterns, Processes, Causes and Consequences

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In 1769 when James Watt patented his improvement of the steam engine invented by Thomas Newcomen, the atmospheric concentration of the main greenhouse gas, carbon dioxide (CO_2), was ~280 ppm. A year later, Joseph Banks sailing on James Cook's *Endeavour* along the Great Barrier Reef, Australia, described with awe: "A Reef such a one as I now speak of is a thing scarcely known in Europe… a wall of Coral rock rising almost perpendicularly out of the unfathomable ocean". By 2006 the atmospheric concentration of CO_2 had increased 36% from the late eighteenth century to 381 ppm (WMO Greenhouse Gas Bulletin, http://www.wmo.ch/pages/prog/arep/gaw/gaw_home_en.html). During the intervening years inventors, engineers, scientists, politicians and entrepreneurs transformed the ways in which the world produced and transported goods, changed societies from agricultural to industrial and manufacturing bases and, most importantly, created and sustained the ever-increasing demand for energy consumption based on fossil fuels – the Industrial Revolution. By 1979 (when the first observations of mass coral bleaching were recorded) the atmospheric CO_2 concentration was 337 ppm. Article 2 of the 1992 UN Framework Convention on Climate Change (http://www.globelaw.com/Climate/fcc.htm) agreed to: "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change" – by then the atmospheric CO_2 concentration was 356 ppm. This was based on recognized concern that: "human activities have been substantially increasing the atmospheric greenhouse gases" and that this "will result in an additional warming of the Earth's surface and atmosphere and may adversely affect natural ecosystems and humankind." The first (1990), second (1995), third (2001) and fourth (Solomon et al. 2007; Parry et al. 2007) Assessment Reports of the Intergovernmental Panel on Climate Change provided mounting evidence of a changing world climate that, with increasing confidence, could be unequivocally attributed to enhanced greenhouse gases due to human activities. These reports also provided evidence that some impacts of climate change on natural ecosystems were already observable and, by the 2001 Assessment, coral reefs were identified as one of a number of "unique and threatened systems" (McCarthy et al. 2001). Human activities since the late eighteenth century have, unwittingly, led to already observable biological responses (coral bleaching) on one of

M.J.H. van Oppen, J.M. Lough (eds.) *Coral Bleaching.*
Ecological Studies 205,

the world's most charismatic ecosystems – coral reefs. This is in addition to what has been termed the "coral reef crisis" where direct local and regional human pressures on coral reef environments (such as over-fishing, destructive fishing, decline in water quality due to land-use changes, nutrient and chemical pollution and development on coasts, mining of coral, etc.) have caused declines in the health of many of the world's coral reef ecosystems (e.g., Wilkinson and Buddemeier 1994; Hughes et al. 2003; Buddemeier et al. 2004).

Tropical coral reefs are the most biologically diverse of marine ecosystems "equalling in beauty and excelling in grandeur the most favourite parterre of the curious florist" (Matthew Flinders, October 1802). They are complex ecosystems at all levels from their geological history, growth and structure, biological adaptation, evolution and biogeography, community structure, organisms and ecosystem metabolism and physical regimes. Coral reefs lay down enormous amounts of calcium carbonate to form massive reef structures that are able to withstand the forces of erosion and create diverse habitats for many organisms. Despite their relatively small area (estimated at only 0.1–0.5% of the ocean floor), coral reefs contain about one-third of the world's marine fish and reef fish account for ~10% of fish consumed by humans. Tens of millions of people in over 100 countries with coral reefs along their coastline depend on the economic and social goods and services provided by these rich ecosystems (Moberg and Folke 1999), valued at U.S.$ 375×10^{12}/year (Pandolfi et al. 2003).

At the heart of these complex ecosystems is an obligate symbiosis between the coral animal and single-celled photosynthetic algae (zooxanthellae) living in the coral tissue. Photosynthetic products provide the coral host with cheap energy. The zooxanthellae also play a role in light-enhanced calcification of scleractinian corals (Barnes and Chalker 1990), allowing the rapid calcification necessary to form reef structures. In return the algae obtain protection and essential nutrients (e.g., nitrogen, inorganic carbon; Davies 1984) from their coral host. The photosynthetic pigments within the algae give the corals their deep brown colour.

Coral bleaching is the term used to describe the loss by the coral animal of all or some of their symbiotic algae and photosynthetic pigments – with the result that the white calcium carbonate skeleton becomes visible through the now translucent tissue layer. Coral bleaching is not a new phenomenon due to global warming. Corals are known to bleach in response to a range of environmental stresses (e.g., low salinity, pollution, unusually high or low water temperatures). In the past, however, such occurrences of bleaching were only observed on small spatial scales in response to localized stresses. What is new and now clearly related to global warming due to the enhanced greenhouse effect is an increase in frequency of large-scale, mass coral bleaching events where entire reefs are affected.

Warming ocean temperatures in the vicinity of coral reefs are linked to the enhanced greenhouse effect and are already having observable consequences for coral ecosystems. Other aspects of projected climate change will also impact coral reefs. Although in some cases less certain (see Parry et al. 2007; Lough 2008; Hoegh-Guldberg et al. 2007) these include:

- More intense tropical cyclones which are a source of localized physical destruction on reefs
- Changes in regional rainfall and river flow regimes with likely more extreme rainfall events and more intense droughts that could affect the periodic extent of freshwater onto reefs
- A gradual rise in sea level that will affect light penetration and also the availability (increase and decrease) of suitable areas for corals to live
- Changes in large-scale and regional atmospheric (e.g., El Niño–Southern Oscillation (ENSO) events; prevailing weather patterns) and ocean circulation patterns that will affect connectivity between reefs
- Changes in ocean chemistry due to about one-third of the excess atmospheric carbon dioxide being absorbed by the oceans, which is lowering their pH and this, in turn, is decreasing the ability of marine calcifying organisms such as corals to form their skeletons and shells

These rapid climate changes are occurring against a backdrop of near-worldwide reef degradation due to local human activities (Hughes et al. 2003; Kleypas and Eakin 2007). In an ideal world, these localized sources of stress to coral reefs should be minimized to enhance the resilience of these remarkable ecosystems to global climate change.

This book fills a vacant niche by bringing together available scientific information on coral bleaching at different space and time scales from the deep geological record through to future projections. By focussing on the many facets of the coral bleaching phenomenon (the most immediate consequence of a changing climate for coral reefs) it builds upon several recent reports and books that highlight the vulnerability of coral reefs in a changing climate (e.g., Salm and Coles 2001; Grimsditch and Salm 2006; Phinney et al. 2006; Aronson 2007; Johnson and Marshall 2007).

The geological history and evolution of the critical coral–algal symbiosis at the heart of coral reefs is introduced by Stanley and van de Schootbrugge (Chap. 2). Oliver et al. (Chap. 3) assess the quality of the largely anecdotal observations of coral bleaching events in space and time and how the reliability of such observations (in the absence of globally widespread and standardized observations) can compromise our ability to determine significant changes in the frequency and occurrence of coral bleaching events. The observational record of the physical environment of coral reefs (particularly sea surface temperatures, SSTs) is much better than the biological record of coral bleaching events. Eakin et al. (Chap. 4) demonstrate how tropical SSTs are warming, the links between unusual warming and ENSO events and the now sophisticated remote sensing products that allow identification of oceanic "hotspots" and conditions conducive to coral bleaching in near-real time. The various tools available for detecting and observing coral bleaching are discussed by Spalding (Chap. 5). These range from remote sensing to the detail necessary in the field extending from whole reefs to individual colonies and, most importantly, the necessity for follow-on surveys to determine the consequences of a coral bleaching event. The possible role that the now recognized diversity of algal symbionts play in conferring thermal resilience on corals is considered by van Oppen et al. (Chap. 6). This also highlights the developing application of genetic analyses to determine algal symbiont diversity and their spatial patterns. Having undergone several bleaching events, is it possible that corals can increase their thermal tolerance? This is addressed by Berkelmans (Chap. 7) who also considers the relationship between thermal bleaching thresholds and the threshold that draws the line between coral's recovery or mortality. McClanahan et al. (Chap. 8) consider the range of consequences of coral bleaching events for corals and erect algae (the sessile benthos of a reef). They tease out the observed range of responses that varies between taxa and also through longer-term effects on reproduction, growth and the incidence of disease, etc. The complex structure of tropical coral reefs, built as a result of the coral–algal symbiosis, provides a habitat for many other motile reef organisms. Pratchett et al. (Chap. 9) assess the consequences of a coral bleaching event for these associated reef organisms and how these effects operate on both short and long time scales. Predicting what might happen to coral reefs in the future depends on understanding coral reef processes and reliably estimating how coral reef climates may change as global climate continues to warm. Donner et al. (Chap. 10) discuss how well current large-scale climate models can provide such information and the possible range of future climates for coral reefs. The findings of the various chapters are synthesized in Chap. 11.

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